Surgery meets fluid dynamics: Into the vortex

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The more I know, the less I understand.

All the things I thought I knew, I'm learning again.

—Don Henley, “The Heart of the Matter”

Among the many wonderful attributes of a career in medicine, and cardiac surgery is no exception, is the never-ending journey of discovery of new knowledge. That such new knowledge often challenges or makes obsolete what may have once been considered solidly established scientific fact only makes the journey more fascinating. The exploration of left ventricular vortex ring formation in hearts after repair of atrioventricular septal defect by Calkoen and colleagues¹ in this month's *Journal* builds about previous work by themselves and others of the same phenomenon in normally structured hearts. Like most investigations into new or partially understood aspects of the physical universe, this article births more questions than it does answers. That is precisely why the work is so compelling and rightly attracts our attention.

Vortices have been exhaustively studied in the field of fluid dynamics, and they possess many remarkable qualities. An extremely energy-efficient platform for transport of fluids, they allow the seamless merging of multiple streams without energy loss. Changes in direction of flow are achieved with similar conservation of power while creating compact zones of flow with uniform directionality and tremendous velocity. The characteristics of vortices have intuitive and powerful application in the context of cardiac structure and function.

The role of vortices in left ventricular physiology was initially investigated in vitro by Bot and colleagues² 25 years ago. Subsequently, 2-dimensional magnetic resonance imaging studies elegantly ratified the concepts of this seminal work. Kilner and colleagues,³ for example, demonstrated radial vortical flow patterns in both the right and left sides of the heart. In the right atrium, superior vena caval inflow is directed slightly anteriorly, circumnavigating the right atrium in systole to join the inferior vena caval stream along the free wall, and together these streams coalesce, looping as if on a roller coaster across

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Central Message

Vortical flow is important to cardiac performance. Surgical interventions have significant and particular impact on this phenomenon.

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the opening tricuspid valve in the rapid-filling phase of early diastole. Similarly, in the filling left ventricle, asymmetric streams of mitral valve inflow merge through vortical flow patterns to become streamlined along the left ventricular free wall and apex, turning toward the left ventricular outflow tract to exit in a nearly opposite direction as systole commences. This elegant conductance of fluid is accomplished with superlative conservation of energy and dramatically increasing velocity.⁴ What's more, some data suggest that these high-speed spinning vortices and their resulting intracavitary streams may serve as epigenetic modulators or inductors of cardiac remodeling processes. The more (one) knows, indeed.

All quite fascinating to be sure, but why, frankly, should a surgeon care? It would seem that this exploration of the physical universe within the left ventricular chamber takes us far away from the clinical realities of, for example, valve repair or replacement, diastolic dysfunction, or chronic heart failure. But does it? Investigators have already documented distinct and impaired flow patterns after mitral valve repair or replacement. Vortices are reversed, duplicated, or abolished altogether, depending on the nature of the prosthesis or repair technique.⁵⁻⁷

It takes little imagination after seeing images of chaotic flow below a ball-in-cage prosthesis to understand that the simple choices surgeons make in the clinical arena may

have an unknowingly profound impact on the far-off world of fluid dynamics and kinetic energy. Congenital heart surgeons well know, for instance, that relatively minor alterations in the structure of a stenotic “parachute” mitral valve can result in significant improvement in mitral inflow physiology and consequently cardiac output. Conversely, at times such patients can have significant clinical deterioration in the face of relatively minor changes in the transmitral gradient. The implication is that something beyond simple mechanical obstruction and derangement in pressure loading is at work.

This investigation of Calkoen and colleagues¹ represents the first time that vortical flow has been characterized in congenitally malformed and repaired hearts. Unfortunately, more severe forms of left atrioventricular valve malformations (parachute valve, double-orifice valve) are underrepresented in the series. There are no hearts with unbalanced atrioventricular septal defect. The challenge presented by these anatomic substrates, and our collective failure to understand why what works in one setting does not work in another, is well documented. The nature of fluid dynamics within the heart, and the role of anatomy and surgical techniques in altering those dynamics, may prove critical to overcoming these challenges. The work reported in this article does not present concrete answers to these

clinical dilemmas. It is too early in our understanding of vortex ring formation for that. But whether through in vitro imaging of theoretical anatomies or surgical interventions or in vivo 4-dimensional magnetic resonance imaging studies, vortical flow mapping and related measures are among the most promising lines of investigation into understanding the mechanical arrangements that optimize left ventricular performance.

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